



Chronology and geochemistry of late Holocene eolian deposits in the Brandon Sand Hills, Manitoba, Canada

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Abstract

Accelerator mass spectrometry and conventional radiocarbon age determinations of organic matter from paleosols indicate that the Brandon Sand Hills area of southern Manitoba has been subjected to recurrent intervals of eolian activity in the past 5000 years. Although precise regional correlations are precluded by dating uncertainties, periods of most notable paleosol development occurred around 2300 to 2000, 1400 to 1000, and 600 to 500 cal yr BP with eolian activity occurring before and after each of these periods. Episodes of eolian activity may correspond to periods of regional drought, whereas paleosols mark periods of increased moisture availability and stabilization by vegetation. The geochemistry of the eolian sands, paleosols and source sediments indicates that partial leaching of carbonates occurs from pedogenesis during humid climatic phases, and that this is probably the primary mechanism of carbonate depletion of eolian sands in this area. Recent trends in sand dune activity from historic aerial photography and early explorers' accounts indicate that the few active dunes that presently exist have stabilized at a rate of 10–20% per decade, despite several severe droughts in the 20th century. This may be attributed to pre-settlement droughts that were more severe than those in historic times although regional dune stabilization may also be related, in part, to the spread of forest cover in the past few hundred years. Crown copyright © 2000 Published by Elsevier Science Ltd. All rights reserved.

1. Introduction

Detailed stratigraphic and geochronologic studies over the past decade have demonstrated that the extensive dune fields of the Great Plains of North America are highly sensitive to climate change and record major droughts of the late Pleistocene and Holocene. Dunes in many parts of this region were long perceived to be relict landforms of full-glacial time (Wright, 1970; Sarnthein, 1978; Kutzbach and Wright, 1985), but it is now known that most dune fields were last active in the Holocene. Stratigraphic studies combined with radiocarbon and luminescence dating methods demonstrate that eolian sands over a wide range of mid-continental North America have been active in the past 3000 years (David, 1971a,

b; Ahlbrandt et al., 1983; Swinehart and Diffendal, 1990; Madole, 1994, 1995; Holliday, 1995a, b, 1997; Forman et al., 1995; Loope et al., 1995; Arbogast, 1996; Muhs et al., 1996, 1997a, b; Wolfe et al., 1995; Stokes and Swinehart, 1997). Furthermore, most of these studies have stratigraphic data indicating multiple periods of eolian activity in the late Holocene. The importance of these studies is that they indicate that eolian sands in this region can be active under an essentially modern climatic regime. This conclusion is underscored by observations of 19th century explorers who reported that many parts of the Great Plains had active dune sands in areas that are presently stable (Muhs and Holliday, 1995; Muhs and Wolfe, 1999).

The Brandon Sand Hills of southwestern Manitoba are located approximately 19 km east of Brandon (Fig. 1), and are comprised of a number of separate dune fields with a total area of 1400 km², including a main dune area of 960 km². Previous chronologic studies of dune activity in the Brandon Sand Hills were conducted by David (1968, 1971a). Radiocarbon dating of the upper

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few centimeters of several humus-rich buried paleosols in a stabilized sand dune at a section on Brookdale Road (MB20, Fig. 2) suggested that the dune first stabilized prior to 3700 ^{14}C yr BP, and that subsequent dune activities occurred sometime after about 3700, 2100, 1500, 900 and 400 ^{14}C yr BP (David, 1971a). David suggested that these periods of dune activity probably affected most of the Brandon Sand Hills and were a consequence of drought. David (1977, 1979) also conducted a preliminary study of the changes in eolian activity in the Brandon Sand Hills using aerial photographs from 1928 to 1969, indicating a general trend toward stabilization of the formerly active dune areas. Despite the intriguing results from these early studies, there have been no recent studies of Holocene eolian activity in the region.

The Brandon Sand Hills are derived from underlying sandy deposits of the Assiniboine delta of Glacial Lake Agassiz (Fig. 1; Elson, 1960). At the Brookdale Road locality, David (1971a) reported a lack of carbonate minerals in dune sands and paleosols, even though the underlying deltaic deposits are carbonate-rich. In contrast, reconnaissance studies in the Brandon Sand Hills by Muhs et al. (1997a) indicated that dunes at other localities contain minor quantities of calcite and dolomite, as is the case with the source sediments. The presence or absence of carbonate mineral has implications for the history of dune activity. In a study of the Minot dune field of North Dakota, approximately 200 km southwest of Brandon, Muhs et al. (1997a) found almost complete

carbonate depletion in dunes derived from similar source sediments. They proposed two mechanisms to explain carbonate depletion in eolian sands. One possibility is that carbonate minerals are lost by leaching and soil formation when eolian sands are stabilized by vegetation. An alternative possibility is that abrasion erodes relatively soft calcite and dolomite minerals to silt sizes during eolian transport via saltation, and the resultant particles are subsequently removed from the dune field by suspension (Pye and Tsoar, 1990). Muhs et al. (1997a) suggested that the former process would imply that the dune field may be stable for extended periods in order for carbonate leaching to result in significant depletion of carbonates throughout the soil profile, whereas the latter would imply extended periods of dune activity to abrade carbonate minerals to silt sizes. At Minot, Muhs et al. (1997a) favored the latter process to explain uniformly low Ca concentrations in eolian sediments because soils developed in non-eolian sediments (glacial, fluvial and lacustrine) surrounding the Minot dune field are all calcareous, sometimes nearly to the surface. They suggested that the mechanism causing carbonate depletion at the Minot dune field may be of less significance in the Brandon Sand Hills, and that a further mineralogical and geochemical study in the Brandon Sand Hills to test this hypothesis would be worthwhile.

The objectives of the present study are: (1) to quantify historic trends in sand dune activity using aerial photography and early explorers accounts, (2) to determine the timing and extent of Holocene eolian activity in the

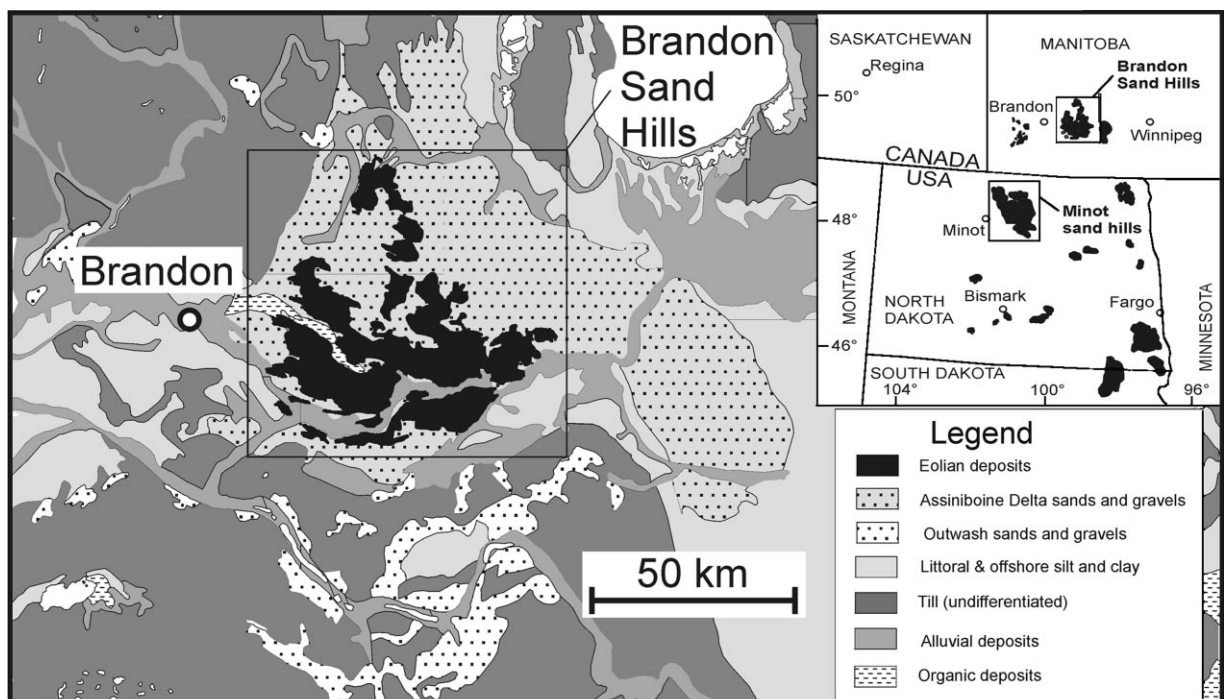


Fig. 1. Location map of the Brandon Sand Hills showing the distribution of eolian deposits and other surficial sediments.

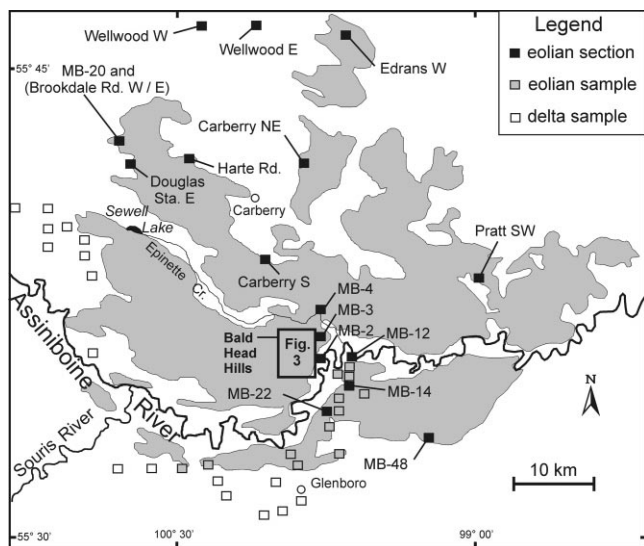


Fig. 2. Locations of eolian sections and geochemical samples within the Brandon Sand Hills.

Brandon Sand Hills by undertaking a geochronologic study within the dune field, and (3) to use geochemical analysis to evaluate the extent to which eolian or soil forming processes have acted on carbonate minerals.

2. Setting

2.1. Climate, vegetation and soils

The Brandon Sand Hills represent one of the northeasternmost dune occurrences on the northern Great Plains (Fig. 1). Precipitation at Brandon averages about 450–470 mm/yr, with about one-quarter falling as snow. The mean annual temperature is about 2°C with July (the warmest month) averaging about 19°C and January (the coldest month) averaging about –18°C. Thus, the area lies within the subhumid climatic zone, with a ratio of precipitation to potential evapotranspiration (P/PE) of about 0.85. Winds are predominantly out of the west and northwest most of the year, but with prominent northeasterly winds also occurring in March, April and May. The net sediment transport direction is towards the southeast, with a drift potential (DP), which is the scalar sum of all sand-moving winds regardless of direction (Fryberger and Dean, 1979), of 582 vector units (VU). The resultant drift potential (RDP), which is the vector sum of all sand-moving winds, is about 240 VU. On the basis of wind energy groupings established by Fryberger and Dean (1979), the Brandon area resides within a high energy regime (DP > 400 VU) as does much of the northern Great Plains region (Muhs and Wolfe, 1999). Most of the Brandon Sand Hills are stabilized by parkland and forest vegetation, with white spruce (*Picea glauca*), aspen

(*Populus tremuloides*), balsam poplar (*Populus balsamifera*) and bur oak (*Quercus macrocarpa*) (Bird, 1927). Larch (*Larix laricina*) is abundant in moist areas.

Soil surveys in the Brandon Sand Hills area show four major soil series developed from eolian sand (Langman, 1989; Podolsky, 1991). Three of these form a drainage continuum (catena or toposequence) on dunes of relatively recent age, whereas the fourth is formed on eolian sand that was probably deposited much earlier. The Shilox series has an LH/Ah/C profile and is classified as an Orthic Regosol (Typic Udipsamment in the US Soil Taxonomy). The Shilox series is areally the most important soil in the Brandon Sand Hills and occurs on all well-drained dune positions. The Onahan series occurs on imperfectly drained positions on the dune landscape and has an LH/Ah/Cgj profile classified as a Gleyed Regosol (Aquic Udipsamment in the US Soil Taxonomy). The Mockry series occurs in poorly drained areas and has a O/Ah/AC/Cca profile classified as a Rego Humic Gleysol (Aquic or Oxyaquic Udipsamment). All three of the soils in this catena show minimal profile development and suggest that most of the eolian landscape in the Brandon Sand Hills is relatively young. In contrast, the Dobbin series has an Ap/Bm/Btj-Bt/BC/C profile, and is developed in both lacustrine and eolian sands. It is classified as an Orthic Dark Gray Chernozem (Typic Argiudoll or Typic Hapludoll). The greater degree of profile development of the Dobbin series suggests that some parts of the Brandon Sand Hills are significantly older than those occupied by the Shilox-Onahan-Mockry catena (Muhs and Wolfe, 1999).

2.2. Surficial geology and geomorphology

The Brandon Sand Hills overlie deltaic deposits derived from the Assiniboine River that flowed into glacial Lake Agassiz at about 11,000 years BP (Manitoba Natural Resources, 1980). Silt and clay deposits surrounding the Assiniboine delta sediments (Fig. 1) are associated with glacial Lake Agassiz, which fluctuated in elevation during deglaciation. Glacial till containing carbonate rock, crystalline-rock and shale pebbles encompasses the area at higher elevations, and was the primary source for the post-glacial fluvial, lacustrine and eolian sediments at lower elevations. There is no bedrock exposed in the area.

The western boundaries of the Brandon Sand Hills are generally smooth and correspond with the areal distribution of sandy deposits in the Assiniboine delta, whereas the eastern boundaries of the dune areas are lobate because of migrating dune complexes extending downwind from the source deposits (David, 1977). Although consisting mostly of stabilized parabolic dunes, the sand hills are also characterized by numerous stabilized blowouts developed either within the underlying deltaic deposits or on formerly stabilized dunes. Most of the

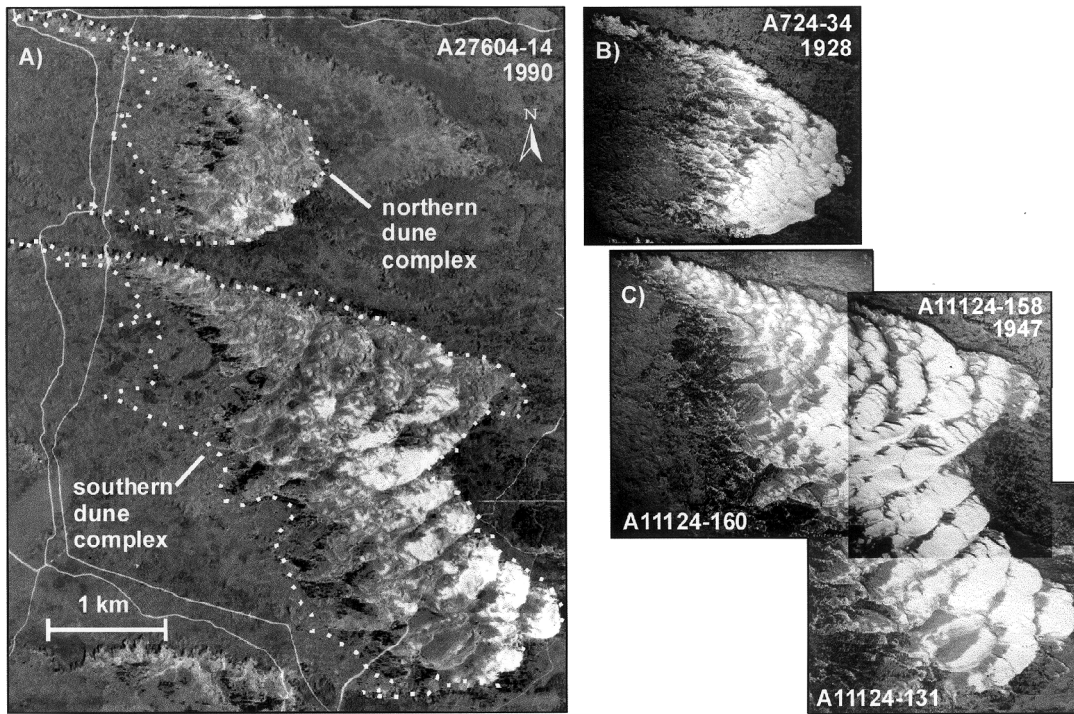


Fig. 3. (A) Aerial photograph taken in 1990 showing bare, active sand in the Bald Head Hills. Dotted line represents outline of dune area in each of the northern and southern dune complexes (NAPL A27604-14). (B) Aerial photograph taken in 1928 of the northern dune complex (NAPL A724-34). (C) Aerial photographs taken in 1947 (earliest complete coverage) of southern dune complex (NAPL A11124-158, 160, 131).

dunes are arranged in a variety of compound forms that have large-scale parabolic patterns oriented towards the east and southeast, indicating net sediment transport from the northwest, similar to that under the modern wind regime.

Only a few areas of the Brandon Sand Hills are presently active. These include a dune complex known locally as the Bald Head Hills lying along the Assiniboine River south of Epinette Creek (Fig. 2). Active dunes form the “heads” of larger parabolic dunes, and appear to be transitional between transverse and parabolic dunes (Fig. 3). In other areas, the south-facing slopes of some dune ridges are partially active. Localized blowouts also occur from disturbances by road construction, grazing and military activities.

3. Methods

3.1. Historic dune activity

Eolian activity, as documented by historical data allow examination of recent trends and possible causes of change. Sand dune activity in the Bald Head Hills area (Fig. 2) between AD 1928 and 1991 is recorded by aerial photographs. Quantitative estimates of dune activity were determined by scanning and digitizing aerial photographs and subsequently calculating the area of bare

sand depicted in each available year. Recent historic trends were compared to the accounts of sand dune activity made by early explorers to assess changes in the area since the late 1700s.

3.2. Geochronology

Radiocarbon analyses of organic matter in buried soils were used to determine the timing of past episodes of paleosol development and eolian activity, and to assess possible regional correlations. Numerous uncertainties are associated with dating soil organic matter with either conventional beta-decay-counting or accelerator mass spectrometry (AMS) radiocarbon techniques. First, organic matter within a soil is derived from a variety of plant and animal sources accumulated over the soil residence time. Second, decay-count radiocarbon dating requires a large volume of material whereas AMS radiocarbon dating utilizes smaller quantities, and is therefore less likely to contain the same temporal spread of dated material. Third, differing ages may be obtained from total, humic, or residue extractions of buried soils (Martin and Johnson, 1995). Detailed studies by Abbott and Stafford (1996) indicate that humic acid extractions minimize both contamination by younger organic acids and recycling of older organic matter. Their results show that humic acid extractions give ^{14}C ages closest to ^{14}C ages of plant macrofossils. In the present study, AMS

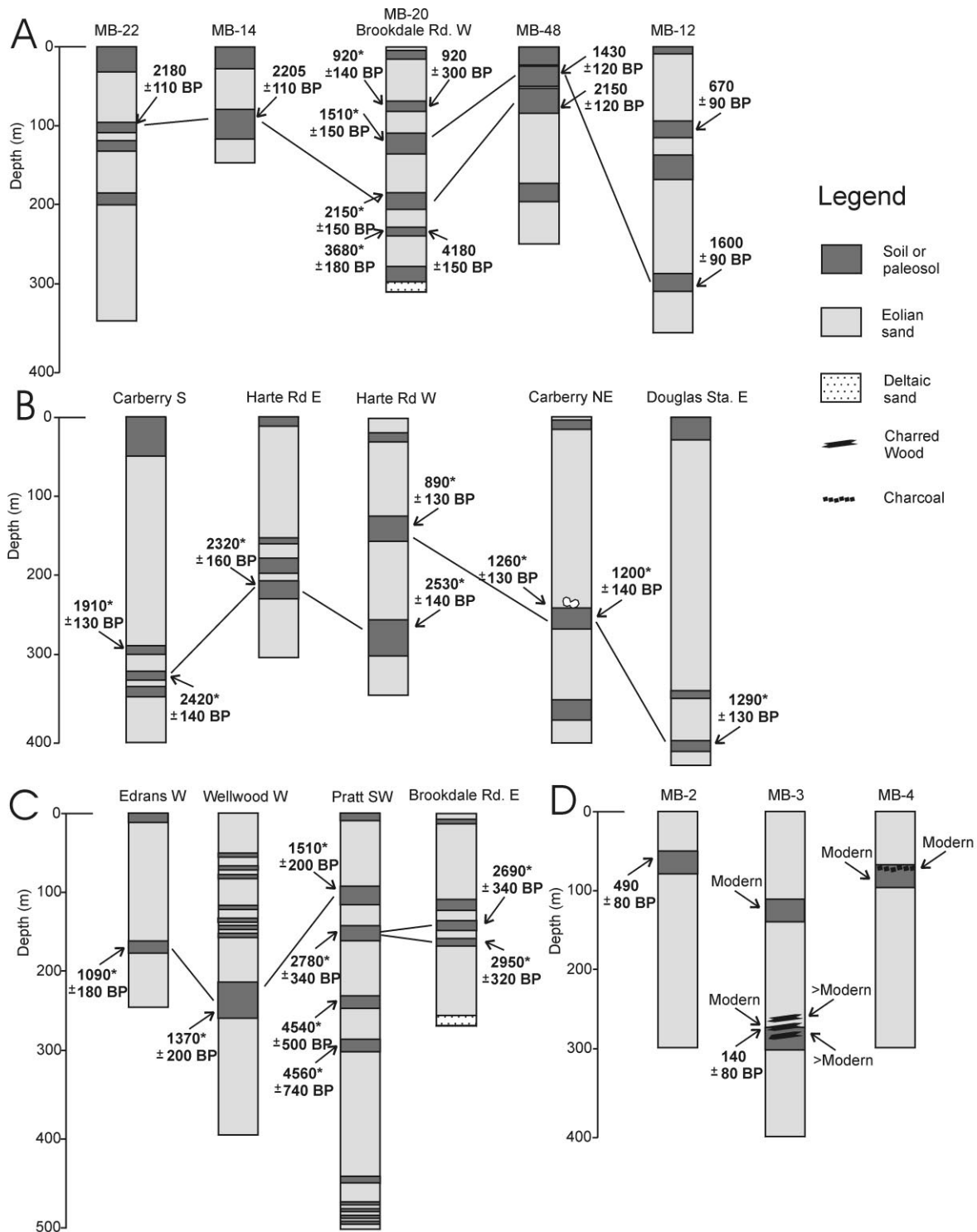


Fig. 4. Stratigraphy of eolian sand, paleosols and associated deposits and radiocarbon ages of organic matter and bones. Asterisk (*) denotes beta-decay-count radiocarbon ages; others are AMS radiocarbon ages. (A) Eolian sections beneath stabilized dunes from this study and including Brookdale Road section of David (1971a); (B) eolian sections beneath stabilized dunes reported by David (1971b); (C) additional eolian sections beneath stabilized dunes observed by David (ca. 1970) and not previously reported; (D) eolian sections beneath recently deposited eolian sands from this study.

radiocarbon ages of buried soils determined from humic acid extractions of organic matter are used together with data from conventional decay-count dating of organic matter extractions from organic-rich horizons in eolian

sands by David (1971a, b; Lowdon and Blake, 1975) and previously unpublished results.

Detailed stratigraphic studies and collection of samples for radiocarbon dating in the Brandon Sand Hills

Table 1
Radiocarbon ages

Locality	Depth (cm)	Soil horizon and sample type	Laboratory number	$\delta^{13}\text{C}^a$ (‰)	Uncalibrated age (years BP) $\pm 2\sigma^b$	Calibrated age (years BP) $\pm 2\sigma$
MB-2	60	2Ab humate	WW-1048, CAMS-35808	– 25e	490 \pm 80	615–495
MB-3	110	2Ab humate	WW-1049, CAMS-35809	– 25e	Modern	Pre-AD 1950
MB-3	285	3Ab humate	WW-1050, CAMS-35810	– 25e	Modern ^c	Post-AD 1950
MB-3	285	3Ab wood	WW-1044, CAMS-35804	– 25e	Modern	Pre-AD 1950
MB-3	285	3Ab wood	WW-1045, CAMS-35805	– 25e	Modern ^c	Post-AD 1950
MB-3	285	3Ab wood	WW-1046, CAMS-35806	– 25e	140 \pm 80	290–0
MB-4	70	2Ab charcoal	WW-1047, CAMS-35807	– 25e	Modern ^c	Post-AD 1950
MB-4	70	2Ab humate	WW-1051, CAMS-35811	– 25e	Modern	Pre-AD 1950
MB-12	115	2Ab humate	WW-1913, CAMS-30704	– 25e	670 \pm 90	675–550
MB-12	390	3Ab humate	WW-1914, CAMS-30705	– 25e	1600 \pm 90	1595–1355
MB-14	75	2Ab humate	WW-1915, CAMS-30706	– 25e	2205 \pm 110	2345–2045
MB-20	75	2Ab humate	WW-1941, CAMS-30732	– 25e	920 \pm 300	1170–560
MB-20	235	5Ab humate	WW-1944, CAMS-30733	– 25e	4180 \pm 150	4865–4450
MB-22	105	2Ab humate	WW-1945, CAMS-30734	– 25e	2180 \pm 110	2340–2005
MB-48	30	2Ab humate	WW-1961, CAMS-30745	– 25e	1430 \pm 120	1415–1260
MB-48	55	3Ab humate	WW-1962, CAMS-30746	– 25e	2150 \pm 120	2330–1950
Brookdale Rd. W	52	2Ab humus	GSC-1091 ^d	– 19.3	430 \pm 130	550–315
Brookdale Rd. W	73	2Ab humus	GSC-954 ^d	– 18.4	920 \pm 140	960–685
Brookdale Rd. W	128	3Ab humus	GSC-953 ^d	– 22.9	1510 \pm 150	1545–1290
Brookdale Rd. W	200	4Ab humus	GSC-950 ^d	– 22.9	2150 \pm 150	2340–1935
Brookdale Rd. W	235	5Ab humus	GSC-949 ^d	– 27.0	3680 \pm 180	4255–3725
Harte Rd.	130	2Ab humus	GSC-976 ^d	– 21.7	890 \pm 130	930–675
Harte Rd.	265	3Ab humus	GSC-981 ^d	– 21.8	2530 \pm 140	2775–2355
Harte Rd.	213	3Ab humus	GSC-817 ^d	– 25e	2320 \pm 160	2710–2130
Carberry S	299	2Ab humus	GSC-970 ^d	– 21.5	1910 \pm 130	1995–1705
Carberry S	320	3Ab humus	GSC-969 ^d	– 21.0	2420 \pm 140	2740–2335
Carberry NE	< 256	2Ab bones	GSC-990 ^d	– 19.1	1260 \pm 130	1295–995
Carberry NE	256	2Ab humus	GSC-931 ^d	– 25.5	1200 \pm 140	1285–955
Douglas Sta. E	396	2Ab humus	GSC-774 ^e	– 25e	1290 \pm 130	1310–1060
Brookdale Rd. E	140	3Ab humus	QU-1378	– 27 \pm 3	2690 \pm 340	3245–2350
Brookdale Rd. E	160	4Ab humus	QU-1377	– 27 \pm 3	2950 \pm 320	3470–2750
Edrans W	170	2Ab humus	QU-1429	– 27 \pm 3	1090 \pm 180	1256–792
Wellwood E	45	2Ab humus	QU-1287	– 27 \pm 3	1310 \pm 660	1920–570
Wellwood W	220	9Ab humus	QU-1286	– 27 \pm 3	1370 \pm 200	1510–1060
Pratt SW	95	2Ab humus	QU-155	– 25e	1510 \pm 200	1685–1265
Pratt SW	150	3Ab humus	QU-316	– 25e	2780 \pm 340	3355–2365
Pratt SW	235	4Ab humus	QU-315	– 25e	4540 \pm 500	5845–4450
Pratt SW	290	5Ab humus	QU-314	– 25e	4560 \pm 740	6170–4160

^aValue of – 25e indicates an estimated value of – 25‰ was used for age normalization.

^bCAMS and QU laboratory ages converted from $\pm 1\sigma$ to $\pm 2\sigma$ for consistency; ages corrected for isotopic fractionation.

^cPost-bomb.

^dReported by David (1971b).

^eReported by Lowdon and Blake (1975).

were conducted along exposures in roadcuts which, in a few cases, were enlarged by localized blowout activity. AMS radiocarbon ages were determined on humic acid extractions from organic matter in paleosol A horizons. Detailed descriptions of the extraction steps are given in Abbott and Stafford (1996), and are summarized in Muhs et al. (1997a). Sample preparation included removal of the > 63 μm fraction, removal of carbonates by a 6M

HCl leach, a 1% KOH extraction at room temperature, removal of clays by centrifugation and filtration, and acidification. Dried and graphitized samples were measured by accelerator mass spectrometry at Lawrence Livermore National Laboratory (CAMS).

To compare decay-count radiocarbon ages on total soil humus with AMS radiocarbon ages of the humic acid extractions, soils previously dated by David (1971a) from

Ah horizons of buried Chernozem soils exposed in a roadcut through the north wing (arm) of a stabilized parabolic sand dune were resampled. The paleosols, separated by beds of humus-free sands, occur in approximately 3 m of dune sand overlying Assiniboine delta sediments (MB-20; Brookdale Rd. W, Fig. 4A). David (1971b) obtained samples from the upper 2–3 cm of each paleosol, except for GSC-949 which was collected 5 cm below the top of the paleosol. Root hairs were removed under a binocular microscope. The organic matter was extracted from the cleaned samples by flotation in distilled water, and the excess water evaporated to produce an organic-rich concentrate. As with most other samples reported by David (1971b; Lowdon and Blake, 1975), the Brookdale samples were not chemically pretreated prior to dating (NaOH-leach and HCl-leach omitted) and were measured using conventional beta-decay-count at the Geological Survey of Canada Radiocarbon Laboratory (GSC).

In addition to the samples discussed above, other unpublished decay-count ages were obtained by David during the 1970s from the Brandon Sand Hills region. The samples were organic matter extractions from paleosols that were obtained using 1 M KOH, heated and cooled to room temperature, precipitated with 10% HCl and separated by centrifugation. The samples were dated using conventional decay-count by the Quebec, Centre de Recherches Minérales, Radiocarbon Laboratory (QU) in the 1970s.

The radiocarbon ages are reported corrected for isotopic fractionation using measured $\delta^{13}\text{C}$ values, or estimated values of -25‰ in the absence of measured values (Table 1). Radiocarbon ages were calibrated to calendar years using the revised CALIB radiocarbon calibration program (Stuiver and Reimer, 1993), in accordance with the radiocarbon age calibration database (Stuiver et al., 1998).

3.3. Geochemistry

Major and trace element geochemistry of eolian sands and hypothesized source sediments can be useful in discriminating potential sediment sources and transport pathways, and in recognizing mineralogical changes over time (Muhs et al., 1995, 1996, 1997a, b). However, unlike the source-sediment uncertainties associated with more geologically complex settings, the Brandon Sand Hills are almost certainly derived from Assiniboine delta sediments as there are no other sandy sediments that could serve as an eolian source in the Brandon area. From regional mapping of eolian and deltaic sediments, it is also clear that the eolian sands of the Brandon Sand Hills have not migrated far from their area of origin (Fig. 1). Therefore, mineralogical and geochemical analyses of eolian and source sediments are used in interpreting mineralogical changes relative to the source sediments

and the extent of eolian activity relative to other dune areas.

Eolian sand samples were collected for geochemical analysis from dune sediments both within and beneath the zones of pedogenesis. With the exception of the Brookdale Road section, there are few exposures of the underlying Assiniboine deltaic sediments. Therefore, most of the source sediments were obtained from the surrounding areas that are mapped as littoral and near-shore sands and gravels comprising the Assiniboine delta (Fig. 2; Manitoba Natural Resources, 1980). Auger samples were collected below the zone of pedogenesis to avoid weathering effects. Pulverized bulk sediment splits were used for all dune sand samples. Because the deltaic samples consist of varying sizes of sand and gravel, samples were dry sieved to obtain the $< 500\text{ }\mu\text{m}$ fraction and subsequently wet sieved to remove the $> 63\text{ }\mu\text{m}$ fraction. The resulting $500\text{--}63\text{ }\mu\text{m}$ fraction, which has a particle-size distribution similar to the eolian sands, was then pulverized to a uniform particle size. Concentrations of Ca, Ti, Sr and Zr were determined by energy-dispersive X-ray fluorescence, following the method of Muhs et al. (1995).

4. Results

4.1. Historic dune activity

Presently, the most active area of the Brandon Sand Hills is the Bald Head Hills (Fig. 2). The larger southern dune complex of the Bald Head Hills occupies approximately 750 ha whereas the northern dune complex covers about 210 ha. In 1990, about 25% of the total area of the southern dune complex was active (Fig. 3A), whereas only about 5% of the northern complex was active. Figs. 3B and C depict the same areas in 1928 and 1947, respectively (the earliest complete photographic coverage for each area). In 1947, about 50% of the southern area was active whereas in 1928, 66% of the northern area was active.

Utilizing all available aerial photographs, it is evident that the area of active sand has decreased continuously at the northern dune complex between 1928 and 1958, from 138 to 23 ha (Fig. 5A). Since 1958, the dune complex has been mostly stabilized, with the total area of active sand fluctuating between 11 and 20 ha. These minor changes may be attributed to annual variation in vegetation cover. In comparison, the area of active sand on the southern dune complex declined from about 400 ha in 1950 to 175 ha in 1990, a decrease of more than 40% in 40 years (Fig. 5A).

Stabilization has occurred at a rate of 10–20% per decade over a period of 40 years (Fig. 5B), and a trend towards net stabilization has continued despite historic droughts such as those in the 1930s and 1980s.

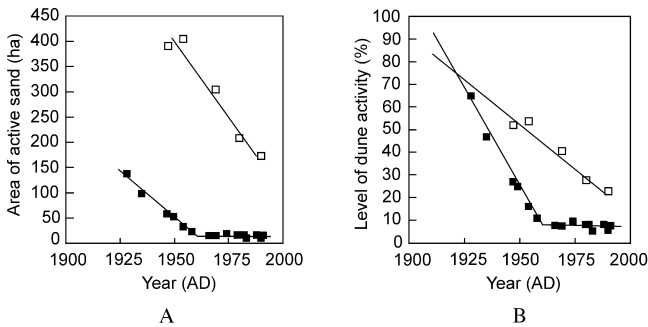


Fig. 5. (A) Area of active sand at the southern (□) and northern (■) dune complexes determined from aerial photographs between 1928 and 1991. (B) Level of dune activity expressed as a percent of the total area of each of the dune complex.

Extrapolating these trends back an additional 30 years suggests that the dune complexes may have been fully active in the early 1900s.

Evidence from earlier explorers supports the assertion that the Bald Head Hills were at least as active, if not more so, than they were at the time of the earliest available photographs of the area. Henry Youle Hind provided an account of the Bald Head Hills on June 23, 1858 (Hind, 1860, pp. 242–243):

On the 23rd, we traversed a region of sand-hills and ridges, until we arrived at Pine Creek, a distance of eight miles from the preceding camp. Here the sand-hills are absolutely bare, and in fact drifting dunes.... The sand dunes were seen reposing on the prairie level about 170 feet above the river. In crossing the country to regain the carts, our course lay across a broad area of drifting sand beautifully ripple-marked... The progress of the dunes is very marked; old hillocks partially covered with herbage are gradually drifted by the prevailing westerly wind to form new ones. Sometimes the area of pure sand was a mile across, but generally not more than half that distance. The largest expanse we saw was near the mouth of Pine Creek, it is called by the Indians "the Devil's Hills," and a more dreary, parched-looking region could scarcely be imagined.

This account is suggestive of fully active dunes, at least as active as those observed in the 1928 aerial photographs. Hind is most likely describing the southern dune complex, which is nearest to the Assiniboine River.

On July 12, 1806, more than 50 years before Hind, Alexander Henry passed through the same area, and wrote the following account (Coues, 1897, Vol. I, p. 297):

At two o'clock we proceeded, and soon came to Montagne du Diable, the tops of which we had seen at Wattap River. This mountain, or rather ridge of barren, sandy hills, is a body of sand several miles in length; the principal hill is on the E., several miles in

circumference, and level on the top, where no kind of vegetation grows. Our path led along the foot of the hill, which appears to be shifting its position eastward. Evidence of this may be seen in the state of the trees on the E. side, where they are so deeply buried in the sands that the very tops of some tall pines just peep through. Westward lies a sandy waste for three miles, where nothing grows but a few stunted epinettes, that tumble down when the sands are blown from about their roots. The principal reason why this body of sand may be said to move eastward is the strong westerly winds which prevail.

Henry's account suggests that the dunes are actively migrating, because the trees (referred to as "pines" but which were more likely spruce) on the eastside of the slipface are buried to their tops. Henry also states that "westward lies a sandy waste for three miles", whereas in the earliest aerial photographs the maximum width of the active dune sand along an eastwest transect does not exceed two miles (~3.2 km) and has subsequently declined. Therefore, Henry's description provides evidence for a level of dune activity in 1806 likely exceeding that in the earliest aerial photographs.

Finally, David Thompson was a surveyor with the Hudson Bay Company and the Northwest Company who explored much of western North America in the late 18th and early 19th centuries. On February 26, 1798, Thompson (in Tyrrell, 1916) describes the Bald Head Hills in only scant detail, and it is unclear whether the level sand dune activity observed by Thompson was greater than that observed by later explorers:

In the afternoon we came to the Manito Hills, they are a low ridge of sand knowls, steep on the west side, but less so on the east side; they have very little grass in a few places, no snow lies on them all winter, which is the reason the Natives call them Manito; or preternatural.

Nevertheless, Thompson's account of "very little grass in a few places" suggests that active dunes were present.

4.2. Geochronology

Three data sets utilizing radiocarbon dating of organic matter extracts from humus-rich paleosol A horizons are used to construct a record of past eolian activity in the region. The data include: (1) AMS radiocarbon ages from the present study determined on humic acid extracts (WW and CAMS laboratory numbers); (2) conventional decay-count radiocarbon ages (GSC laboratory numbers) of organic matter extracts published by David (1971a,b) and in Lowdon and Blake (1975); and (3) conventional decay-count radiocarbon ages (QU lab numbers) of organic matter extracts obtained by David

in the 1970s and not previously published (Table 1). Because of later improvements in laboratory methods, the age uncertainty associated with the QU ages is about twice that of the other ages.

Natural exposures, roadcuts and auger borings show that the upper few meters of eolian sand record multiple episodes of deposition (Fig. 4). Periods of stability are marked by paleosols with Ah/C profiles, similar to modern soils on stabilized dunes. Certain modern soils under spruce have Ae horizons, but all modern soils examined herein, nevertheless, show a minimal degree of profile development. A minimal degree of soil development in both paleosols and modern soils indicates that past periods of stability, as well as the modern period of stability, have been relatively short.

An AMS radiocarbon age ($\pm 2\sigma$) of 920 ± 300 ^{14}C yr BP was obtained from the paleosol that David (1971a) previously dated to 920 ± 140 ^{14}C yr BP (Table 1) with the decay-count method. Although no significance should be placed on the result that the apparent ages are precisely the same, the results do indicate that the two methods of dating produced very similar results. This result may be due, in part, to the relatively short residence time of these paleosols. An age of 4180 ± 150 ^{14}C yr BP was obtained from a paleosol that was dated by David (1971a) at 3680 ± 180 ^{14}C yr BP. In this case, the calibrated ages do not overlap at $\pm 2\sigma$, although they differ by only about 200 years. The fact that the decay-count radiocarbon age is younger than the AMS age may be due to incorporation of younger mobile carbon leached from paleosols higher in the profile. Whereas the humic acid extraction method of Abbott and Stafford (1996) minimizes the inclusion of recycled and mobile carbon, organic matter extracts from larger samples may include these additional materials. Indeed, David (1971b) considered this possibility for other paleosols dated in the Brandon Sand Hills, including the lower paleosols at Harte Rd. E and Carberry S (Fig. 4B). Nevertheless, the general similarity in ages derived from the two methods indicates that, in these cases, conventional decay-count radiocarbon ages of organic matter extracts obtained by David (1971a, b) are comparable to those obtained from AMS dating of the humic acid extracts using the Abbott and Stafford (1996) method.

Radiocarbon ages support the pedologic interpretation that the Brandon Sand Hills have been active in the late Holocene (Table 1; Fig. 4). Stratigraphic and radiocarbon data indicate that the Brandon Sand Hills have been active several times in the past 5000 ^{14}C yr BP (Fig. 4). The oldest radiocarbon ages were obtained from the Pratt and Brookdale Road sections, with an age of ~ 4500 ^{14}C yr BP (4160–6170 cal yr BP) at Pratt and between 3680 ± 180 to 4180 ± 150 ^{14}C yr BP (3725–4865 cal yr BP) at Brookdale, with evidence of eolian activity prior to and after these periods of stability. There is also evidence for several regionally correlative periods

of stability between episodes of eolian sand activity in the Brandon Sand Hills. Paleosol development with closely similar ages of 2180 ± 110 , 2205 ± 110 , 2150 ± 120 , and 2150 ± 150 ^{14}C yr BP (1935–2345 cal yr BP) are recorded at sections MB-22, 14, 48 and Brookdale Rd. W, respectively. These paleosols also overlap in age with four paleosols at three other sections (Carberry S; Harte Rd E and Harte Rd W), with ages of 1910 ± 130 ; 2420 ± 140 ; 2320 ± 160 and 2530 ± 140 ^{14}C yr BP (1710–2775 cal yr BP) and, stratigraphically, with the Pratt SW and Brookdale Rd. E sections (2780 ± 340 ; 2690 ± 340 and 2950 ± 320 ^{14}C yr BP; calibrated age range 2350–3470 cal yr BP). Thus, two or more periods of stability likely occurred between about 1700 and 3500 cal yr BP, with the strongest evidence for stability occurring around 2000–2300 cal yr BP.

All sections record periods of eolian activity occurring episodically in the past 2000 years. There are few paleosols between 1900 and 1600 cal yr BP, whereas many sections record paleosols between 1000 and 1400 cal yr BP, followed by eolian activity. Eolian activity also occurred within the past 500 years and has continued until very recently, despite minimal dune activity at present. Three sections studied (MB-2, MB-3, and MB-4) yielded radiocarbon activity that is greater than modern (i.e., AD 1950), indicating contamination of these materials by very recent (“post-bomb”, or post-1950) migration of ^{14}C , probably from downward-percolating soil waters. However, the other materials analyzed from these three sections do not have evidence of bomb-derived ^{14}C and therefore yield useful ages. The paleosol at MB-2 gave an age of 490 ± 80 ^{14}C yr BP, indicating a period of eolian sand deposition sometime in the past ~ 500 years. Humic acids from the second buried soil at MB-3 indicate two periods of eolian activity since 140 ± 80 ^{14}C yr BP (0–288 cal yr BP), and the modern (but pre-bomb) radiocarbon age of the paleosol at MB-4 indicates very recent eolian sand deposition at that locality. In contrast, the Brandon Sand Hills region presently appears to be in a condition of relative stability.

4.3. Geochemistry

Concentrations of chemically immobile elements such as Ti and Zr, found in heavy minerals, show a roughly linear relation to each other, with closely similar Ti/Zr values in eolian and deltaic sediments (Fig. 6A). These observations are consistent with earlier results of Muhs et al. (1997a), and with the interpretation that the Assiniboine delta sediments are the source for the Brandon Sand Hills.

Some of the Brandon dune sands show a depletion in calcium relative to that found in the source sediments whereas others have a significant overlap with Ca concentrations in the deltaic sediments. X-ray diffraction analyses show that calcium, although present in calcic

plagioclase and other minerals, is primarily associated with carbonate minerals such as calcite and dolomite in these sediments. It occurs in concentrations generally ranging from 3 to 10% in the deltaic sediments (Fig. 6B). Many of the dune sands have low ($< 2\%$) Ca concentrations whereas others have concentrations that differ little from the source sediments. Samples with less than approximately 3% Ca do not have detectable quantities of carbonate minerals. Sr, which generally tends to follow Ca, shows no significant difference in the Ca-depleted sands. This apparent bimodal concentration of Ca explains what appeared to be differing results obtained by David (1971a), who found dune sands at the Brookdale Road section depleted in carbonates, and Muhs et al. (1997a), who found that dune sands sampled between Carberry and the Bald Head Hills had measurable amounts of carbonates.

Concentrations of Ca in association with the modern and buried soils suggests that leaching is the primary mechanism for carbonate mineral depletion in the Brandon Sand Hills (Fig. 7). Concentrations of Ca examined as function of depth show that the modern soil and

paleosol A horizons are typically depleted in Ca, whereas the intervening C horizons (eolian sand) contain concentrations within the range of the source sands. In several profiles (MB-22 and MB-48), although Ca concentrations are depleted within the paleosols, they increase with depth beneath the buried soils.

5. Discussion

5.1. Historic dune activity

Early accounts of the Bald Head Hills establish that the dunes were at least as active in AD 1858 and 1806 as they were in 1928, and probably more so. These accounts lead to the conclusion that historic dune activity in the area, rather than being due to historic droughts such as that of the 1930s, could have been a product of events predating the 1900s and possibly pre-dating the 1800s. Furthermore, the rapid stabilization in dune activity observed since 1928 is evidently a phenomenon primarily related to this century. Rather than suggesting that dune activity is not sensitive to drought, these observations indicate that dune activity in the early part of this century may have been carried over from an earlier period of greater eolian activity, possibly induced by more intense droughts than observed in the 20th century. In southwestern Saskatchewan, geochronological evidence indicates that eolian activity was widespread in many areas within the last 200 years (David et al., 1999; Wolfe et al., 1995) and that eolian activity has also diminished throughout the 20th century. Dendroclimatological records suggest that the widespread dune activity in Saskatchewan may be related to multiple droughts in the 1700s, culminating in widespread drought in the 1790s (Case and MacDonald, 1995; MacDonald and Case, 2000). If the timing of droughts in southern Manitoba

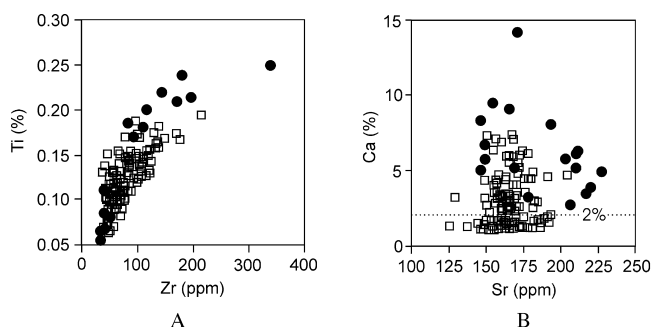


Fig. 6. Comparison of (A) Ti and Zr, and (B) Ca and Sr concentrations in eolian sediments (□) and delta source sediments (●; 500–63 μm).

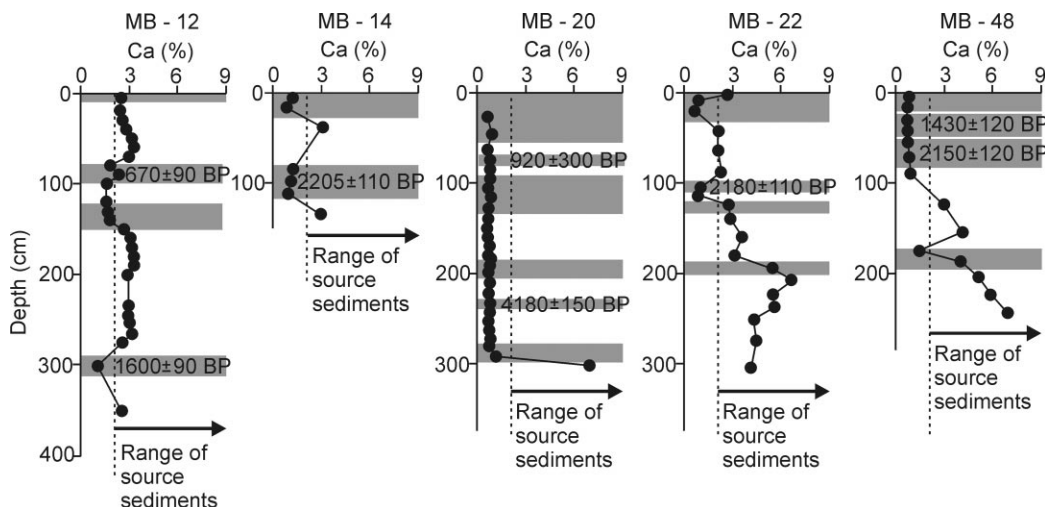


Fig. 7. Concentration of Ca as a function of depth in five eolian sections in the Brandon Sand Hills.

was synchronous with Saskatchewan this may have resulted in increased dune activity at the same time.

5.2. Geochronology and regional correlations

Although the Brandon Sand Hills are mostly stabilized at present, stratigraphic sections throughout the region indicate that eolian activity has occurred several times in the late Holocene. The occurrence of minimally developed soils with Ah/AC/C profiles over much of the Brandon Sand Hills further suggests a particularly young age for this modern surface in view of soil chronosequence studies that have been conducted elsewhere in the southern boreal forest and oak-savanna of Canada. Near Hudson Bay, James Bay, and in Pinery Provincial Park, Ontario, soils with Ae/BF/C or Ae/BM/C profiles have developed in less than 2500 yr (Protz et al., 1984, 1988; VandenBygaart and Protz, 1995), under precipitation regimes ranging from 500 to 850 mm/yr. In the drier grasslands of the central and southern Great Plains, soils with only Ah/AC/C profiles are developed on dunes of late Holocene age (Muhs, 1985; Holliday, 1990, 1995a; Madole, 1994, 1995; Muhs et al., 1996, 1997a, b; Arbogast, 1996; Muhs and Wolfe, 1999). These comparisons suggest that the minimally developed soils of the Brandon Sand Hills indicate that much of the dune field has been active in the past 2–3 millennia.

The chronology and frequency of paleosol development derived from radiocarbon dating suggests that there have been at least five periods of relative stability interspersed by four periods of eolian activity in the last ~ 5000 cal yr BP (Fig. 8). These four periods of eolian activity in the Brandon Sand Hills may correspond to records of relative aridity found elsewhere in the northern Great Plains. Although geochronological controls preclude precise correlation, a diatom-based record of salinity changes in Devils Lake, North Dakota (~ 180 km south of the Brandon Sand Hills) suggests at least five major periods of relatively dry conditions in the

past 5000 ^{14}C yr BP (Fritz et al., 1991). The early part of Brandon Sand Hills chronology correlates well with that from Kenosee Lake Saskatchewan, about 200 km west of Brandon (Vance et al., 1997) with a period of high salinity between ca. 4100 and 3000 ^{14}C yr BP followed by a rapid rise in lake level between ca. 3000 and 2300 ^{14}C yr BP. This rise in lake level closely corresponds to a time of increasing paleosol formation in the Brandon Sand Hills. In the past 2300 years, several periods of relative aridity in the northern Great Plains have also occurred, as evident from the records at Moon Lake not far from Devils Lake, North Dakota (Laird et al., 1996) and Kenosee Lake (Vance et al., 1997). At Kenosee Lake, lake draw-down and increased salinities prior to ca. 600 ^{14}C yr BP (Vance et al., 1997) match a decline in paleosol frequency between 1000 and 600 cal yr BP in the Brandon Sand Hills. Because salinity in these lakes is controlled largely by the overall regional moisture balance, as measured by precipitation and evapotranspiration, it is possible that they are responding to the same climatic controls that bring about dune activation and stabilization.

5.3. Geochemistry and carbonate depletion

Carbonate profiles (Fig. 7) are consistent with trends expected if leaching of carbonates was the main mechanism occurring at the time each soil was at the surface. An exception to this general trend is the Ca profile at the Brookdale section (MB-20). Here, the dune sands exhibit uniformly low Ca concentrations with depth, with only the lowermost delta sediments containing higher concentrations. Low Ca concentrations within the C horizon sands at the Brookdale section are not consistent with the other profiles, nor with the trend expected from soil leaching. However, it appears unlikely that the entire profile could have been leached of carbonates subsequent to deposition while the other profiles remained incompletely leached. A more likely explanation is that the

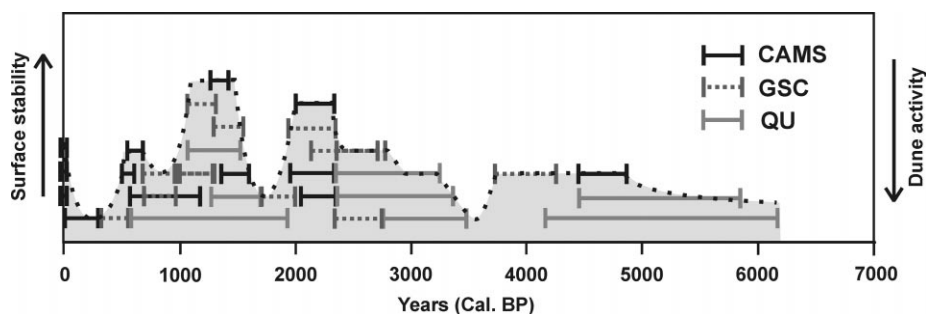


Fig. 8. Frequency of calibrated radiocarbon ages from paleosols within dune sands in the Brandon Sand Hills region depicting relative phases of surface stability and (inferred) periods of dune activity in the last 6000 years. The length of a horizontal bar is indicative of the age uncertainty at 2σ only, and not of the period of soil development. The dotted line brackets the trend in paleosol abundance, and a greater abundance is equated with increased surface stability.

source sands were previously depleted in Ca. In this scenario, surface sands previously leached through pedogenesis were subsequently reworked and redeposited by eolian activity at this locality.

The interpretation that carbonates in the Brandon Sand Hills are depleted primarily by leaching rather than eolian abrasion contrasts with the Minot dune field to the south. This suggests that, overall, the Brandon dune field may have been stable for longer periods over the Holocene than has the Minot dune field. Presently, the Minot dune field is in an area that is slightly more arid than Brandon (P/PE of 0.78 vs. 0.85), although the differences are slight enough that such a significant difference in long-term dune field history is unexpected. If so, then it implies that eolian activity in the northern Great Plains may have a narrow climatic threshold, and that the Minot dune field is near enough to this critical threshold such that a slight increase in aridity brings about a significant increase in dune activity.

5.4. Controls of late Holocene eolian activity

Studies of both active and stabilized dune fields and regional climate in Australia, Africa, and North America suggest that one of the most important controls of dune activity is overall moisture balance, commonly estimated by the ratio of precipitation to potential evapotranspiration (Ash and Wasson, 1983; Lancaster, 1988; Muhs and Maat, 1993; Muhs and Holliday, 1995; Wolfe, 1997). In addition to the direct effect moisture has on dune stability through particle-to-particle cohesion (David, 1978, 1979), moisture plays a critical role in degree of vegetation cover, which has both direct and feedback effects that enhance dune stability (Muhs and Wolfe, 1999). On the basis of these studies, we propose that periods of Holocene eolian activity and stability in the Brandon Sand Hills (Fig. 8) correspond to periods of regional drought and increased moisture, respectively. This hypothesis is supported by the correlation between periods of Brandon Sand Hills eolian activity (based on bracketing radiocarbon ages of paleosols reported here) and periods of high salinity recorded in nearby North Dakota and Saskatchewan lakes (Fritz et al., 1991; Laird et al., 1996; Vance et al., 1997).

The depth functions for calcium in the stratigraphic sections of the Brandon Sand Hills suggest that periods of dune stability occur when the climate is not only humid enough to support vegetation on the dunes, but also humid enough for through-leaching of carbonates in soils. Such conditions characterize the modern climate of the region, which is presently adequate to support a southern outlier of boreal forest dominated by white spruce. The overall moisture balance, as measured by P/PE (0.85 for Brandon) indicates a subhumid regime that is slightly moisture deficient, but still is close enough

to a positive balance that vegetation remains healthy and soluble elements are leached in soils.

Despite the present forest cover, all of the paleosols examined have profiles typical of prairie. None of the buried soils contain Ae horizons, which form rapidly in sands under boreal forest (Protz et al., 1984, 1988), but only rarely form under grass, regardless of the amount of time available for pedogenesis. These observations suggest that the present forest cover on the stabilized dunes may be a recent phenomenon, and could be related to climatic variations in the past millennium, or to more recent changes in land use associated with European settlement. Whereas fire suppression may have played a role in forest maintenance since the time of European settlement, historic accounts by Alexander Henry and Henry Hind indicate that conifers were in the area prior to the time of major settlement in the latter part of the 19th century. At Kenosee Lake, Saskatchewan high lake levels and freshwater conditions as well as an increase in *Betula* (birch) pollen attributed to paludification as recently as 600 years ago, may be related to wetter climatic conditions during the Little Ice Age (Vance et al., 1997). However, this conclusion contrasts with findings of Little Ice Age aridity at Devils Lake, North Dakota (Fritz et al., 1994), also in the northern Great Plains. These differing observations of aridity on the northern Great Plains support the suggestion that the Minot dune field may have experienced greater eolian activity in the Holocene than the Brandon Sand Hills. This suggests that differing moisture balances during the late Holocene have played a significant role on dune activity in northern Great Plains. A proposed very late Holocene shift in vegetation regime from prairie to forest associated with wetter conditions in the Brandon Sand Hills is the subject of ongoing study.

6. Conclusions

The presence of minimally developed soils with Ah/Ac/C profiles over much of the area suggests that most of the stabilized eolian landscape in the Brandon Sand Hills is relatively young. Similarly, aerial photographs and early explorers accounts indicate that dune activity was greater in the 19th century than today. Furthermore, the dunes have stabilized at a rate of 10–20% per decade.

Decay-count and AMS radiocarbon dating of paleosols from eolian sections indicate that all areas of the Brandon Sand Hills have been subjected to eolian activity several times in the past ~ 5000 yr. Although regionally correlative periods of activity and stability have not necessarily occurred, several periods of notable paleosol development occurred around 2300–2000, 1400–1000 and 600–500 cal yr BP. Eolian activity occurred

between these periods, and may correspond to droughts recorded in northern Great Plains lakes.

The geochemistry of the eolian sands, paleosols and source sediments indicates that partial leaching of carbonates has occurred through pedogenesis, and that this is probably the primary mechanism of carbonate depletion of eolian sands in the area. This contrasts with the Minot dune field to the south, where a greater frequency of eolian activity has apparently depleted carbonate minerals by means of abrasion. Carbonate depletion, although primarily restricted to the Ah horizon of eolian sands, may occur relatively rapidly in this area during more humid climatic intervals such as at present. Recycling of carbonate-depleted near-surface sands by wind erosion may occasionally result in uniformly depleted profiles of redeposited sands in dunes.

Moisture balance, as defined by the ratio of precipitation to evapotranspiration, has probably played a significant role in the Brandon Sand Hills area. Variations in moisture balance have likely influenced the degree of pedogenesis and the associated changes in vegetation cover and type, which have further influenced dune activity and stability throughout the Holocene. Furthermore, regional variations in moisture balance on the northern Great Plains have likely resulted in differing histories of eolian activity, possibly over relatively short distances, where climatic thresholds are crossed.

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